Multiphase ac Loss Mechanisms in HTS Prototype Multistrand Conductors

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Abstract—We report on multiphase ac losses in four-layer prototype multi-strand conductors (PMCs) wound from high temperature superconductor (HTS) tape provided by American Superconductor Corporation. "Two-phase" losses are induced with no current flowing in the PMC but with an ac magnetic field generated by currents flowing in the two normal conductors arranged at the remaining corners of an equilateral triangle forming a three-phase configuration. This is a typical configuration that a power cable of the "warm dielectric" design could have. The losses were measured at 65 to 76 K, in a frequency range from 10 to 180 Hz, and for currents from 600 to 1600 Arms. We compare the losses for two PMCs, one wound conventionally with equal pitch angles for all layers and the second wound to achieve uniform current distribution (UCD) among the layers. The UCD method results in reduced single-phase losses at currents greater than about 1/2 of the critical current. However, the two-phase losses are somewhat larger for the PMC wound by the UCD method. We investigated this difference empirically and theoretically.

Index Terms—Superconducting power transmission lines, alternating current losses, multiphase losses, high temperature superconductors.

I. INTRODUCTION

SUPERCONDUCTING power transmission lines are being considered by the electric utility industry as a replacement and upgrade for existing oil-cooled copper underground-transmission lines in urban areas. In these areas, increasing loads require more current carrying capability. Because superconducting transmission lines can carry as much as twice the current as existing copper lines and can be retrofitted into the same conduits, they offer a significant economic advantage in that they require no expensive new construction.

One of the most important issues in superconducting transmission line engineering design and application is the ac losses these conductors incur at power-line frequencies, both from the self magnetic field of the conductor, and, in certain designs, from the ac magnetic fields generated by the other two phases of a three-phase line.

We report here on the "two-phase" ac losses resulting from the influence of the other two phases of a three-phase superconducting power transmission line on the phase under test. There are several designs for retrofitting underground power transmission lines with high temperature superconductor (HTS) cables. In the "cold dielectric" design each superconducting phase is surrounded by a superconducting shield. Outside of the shield, therefore, there is no net magnetic field, so that there is no influence of one phase on the others. In the "warm dielectric" design there is no coaxial shield around each phase, thus reducing the use of HTS material significantly, but at the expense of interaction among the phases. If the conductors are relatively far apart, e.g., 20 to 30 cm or more, there is little effect of the fields from the other phase conductors [1]. This is expected to be the case for the Detroit Edison - Superconductivity Partnership Initiative (SPI) cable retrofit project sponsored by the U.S. Department of Energy. Here, the major loss component is the single-phase loss with transport current flowing only in the PMC. However, for installations where space is at a premium, typically all three phase conductors are installed in a single conduit with conductor spacing on the order of 10 cm, and the influence of the other phases does need to be considered.

We have measured the ac losses of two prototype multistrand conductors (PMCs) constructed as potential candidates for the Detroit Edison project. The project is a retrofit of nine underground copper cables with three HTS cables (three phase) designed to carry 2400 Arms at 24 kV for a distance of 130 m within the Frisbie substation in downtown Detroit, MI. The PMCs tested differ primarily in winding design. We will compare and contrast the performance of the two conductors.

II. EXPERIMENTAL

A. Experimental Apparatus and Procedure

Voltage measurements have been used by a number of groups to measure the single-phase ac losses of power transmission line prototypes. However, complications arise as to placement of voltage contacts and interpretation of data when a PMC is subjected to external magnetic fields that may drive currents in circular paths that do not cause a voltage to appear at the contacts but do result in losses. This is in particular the case when the multiphase losses are to be measured in a PMC of the warm dielectric design.

For this reason, we chose to use a calorimetric technique for measuring the ac losses. Reference [2] contains

substantial detail about the calorimeter construction and operation. Briefly, in this technique, the PMC is thermally isolated except at the two ends. Heat generated uniformly in the conductor results in a parabolic temperature profile along the conductor length. This profile is measured with platinum resistance thermometers and fitted to the equation:

$$q_L = 8kA\Delta T_m/L^2, \qquad (1)$$

where q_L is the heat generation (loss) per unit length of the conductor, k is the effective thermal conductivity along the length of the PMC, A is the conductor cross-sectional area, ΔT_m is the temperature difference between the ends and the midpoint of the conductor, and L is the conductor length. The factor kA is determined independently by measuring the temperature gradient along the conductor when a known amount of power is generated by a bifilarly wound heater located at the midpoint. Because the determination of the ac-power loss is independent of the temperatures of the conductor ends, Joule heating at the normal/superconductor junction, which raises the temperature of the ends of the PMC, has little effect on the accuracy of the measurement. The loss is corrected for the temperature variation along the PMC [2].

The PMC is contained in a G-10 (glass epoxy) vacuum jacket with the ends (the current leads) cooled by the surrounding liquid nitrogen. The other two phases in the three-phase configuration are normal copper conductors, with the three phases arranged at the vertices of an equilateral triangle 10 or 20 cm on a side. Because the vacuum jacket of the PMC is a nonconductor, the PMC is affected by the magnetic field generated by the other two phases, similar to the environment present in a warm dielectric three-phase cable. The temperature of the liquid nitrogen bath can be varied from about 75 K to 64 K by controlling the pressure of the bath using a vacuum pump and pressure regulator.

ac current is supplied by a standard, industrial-type 20 kW ac induction-motor drive modified for use as a variable-frequency power source. The output of the variable frequency source is connected to a 480 V / 5 V, 41.7 A / 4000 A, three-phase, step-down transformer connected in a delta/wye configuration. The power supply is typically operated over the frequency range of about 10 Hz to 180 Hz. It can supply currents up to 3000 Arms near 60 Hz, but is limited to lower levels (~1000 Arms) at low frequency by transformer core saturation and at high frequency by the transformer impedance. The current source performs well both under single-phase and balanced three-phase operation.

B. Cable

The prototype multistrand conductors (PMCs) were each wound by Pirelli from the same advanced Bi-2223/Ag sheath multifilamentary tape manufactured by American Superconductor Corporation. PMC 4LA was wound conventionally with equal and opposite pitch angles in alternate layers. PMC 4LB was wound to achieve the same inductance for each layer by adjustment of the pitch angle for each layer. This method was first proposed by the group at Siemens [3], [4]. The result of this winding technique is to achieve uniform current distribution (UCD) among the layers of the PMC. Parameters of the PMCs are listed in Table I.

TABLE I.
PMC PARAMETERS

Condition	4LA	4LB
I_c at 77 K	6000 A	5200 A
Winding Pattern	~±30° pitch angle	adjusted angles
Tapes/layer	~20	~20
Dimensions	30 mm x 1 m core	30 mm x 1 m core

III. RESULTS AND DISCUSSION

A comparison of the single-phase losses of PMCs 4LA and 4LB at 76 K and 60 Hz is shown in Fig. 1. The losses depend on the current as a power law with an exponent n near 3. According to the uniform current distribution (UCD) model, magnetic flux penetrates into each of the four layers of PMC 4LB even at the lowest currents. In contrast, the monoblock model predicts that at low currents, flux will only penetrate the outer layers of PMC 4LA. Thus, the losses are lower for 4LA at low currents. At high current levels ($\sim \geq I_c/2$), on the other hand, the outer layers of PMC 4LA will carry current densities close to the critical current density of the layers, while the inner layers will carry lower current densities. Because the ac losses are proportional to I^3/I_c at this current level, the losses in the outer layers are very large and dominate. For 4LB, with uniform current distribution among the layers, the maximum current in the outer layer will be lower than for 4LA and therefore the losses will be lower at high currents, in the operating range for applications. For these two conductors, the crossover current is about 1300 Arms at 76 K and 60 Hz.

The two-phase losses as a function of current for PMC 4LA are shown in Fig. 2. Within the critical state model for hysteretic (or penetration) losses q_p in an elliptically shaped superconductor [5], the expected dependencies are

$$q_p = (B_m^3/4\mu_0)(\omega/I_c), \qquad (2)$$

where B_m is the applied magnetic field, from the current flowing in the two other phase conductors for this case, and ω is the angular frequency. Thus, the critical-state model predicts that the two-phase losses should be linear in the frequency, inversely proportional to I_c, and cubic in the applied field (current). The ratio of frequencies 140/60 is 2.33. The critical current I_c depends on temperature; the ratio $I_c(65 \text{ K})/I_c(76 \text{ K})$ is 1.66 for this superconductor tape.
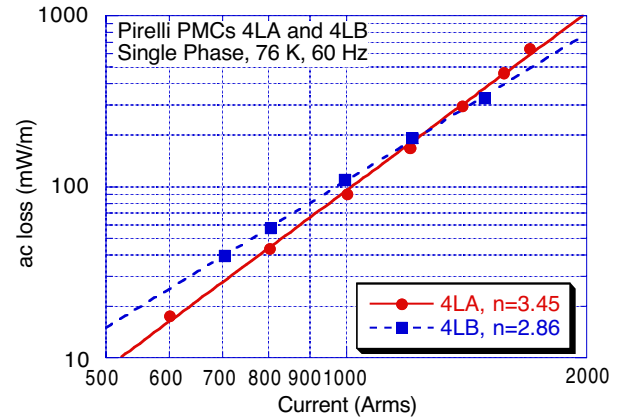

Fig. 1. Comparison of single-phase losses as a function of transport current for 4LA and 4LB, with nonuniform and uniform current distribution, respectively. The n values are the exponents of the power-law fits to the data shown in the figure.
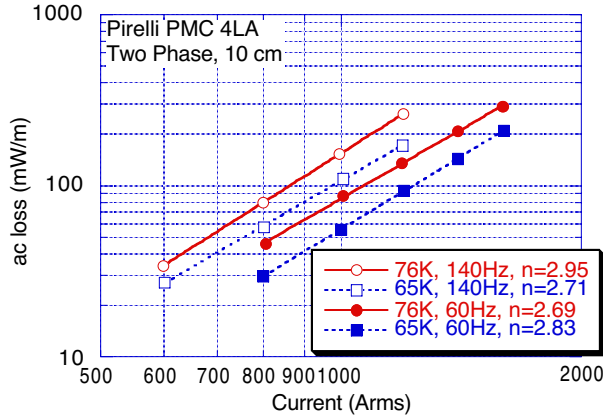
Fig. 2. Two-phase losses for PMC 4LA as a function of current at a conductor spacing of 10 cm and for the temperatures and frequencies indicated. The *n* values are the exponents of the power-law fits to the data shown in the figure.

TABLE II.
RATIOS OF LOSSES *q* COMPARED TO CRITICAL STATE MODEL VALUES

Condition	4LA	4LB	Model Value
$q(76\ K)/q(65\ K)$ @ 60 Hz	1.56	1.39	1.66
$q(76\ K)/q(65\ K)$ @ 140 Hz	1.46	1.37	1.66
$q(140\ Hz)/\ q(60\ Hz)$ @ 76K	1.79	2.22	2.33
$q(140\ Hz)/\ q(60\ Hz)$ @ 65K	1.91	2.20	2.33

The measured and the calculated values for the critical state model are shown in Table II. The temperature dependence of the two-phase losses for 4LA is somewhat less than the model predicts. The frequency dependence is significantly less than the model value. At each condition of temperature and frequency, the power-law exponent *n* is always less than 3.

These discrepancies from the critical state model dependence on various parameters suggested the presence of an additional loss term. Measurement [6] of the frequency dependence of the two-phase loss at fixed current level gave further evidence of the presence of a loss term nonlinear in the frequency and quadratic in the applied field:

$$q_C = (B_m^2/4\mu_0)(\omega^2\tau)/(\omega^2\tau^2+1), \qquad (3)$$

where q_c is the coupling loss [7], and τ is a characteristic time constant. This loss is caused by currents forced to flow through the normal (nonsuperconducting) matrix material surrounding the HTS filaments in the Bi-2223 tape.

The two loss contributions can be visualized as follows: for each half-pitch length of helically wound tape, the applied magnetic field forces supercurrents to flow in opposite directions along the filaments at each side of the tape. The supercurrent direction is reversed for the adjacent half pitch. These supercurrents generate the hysteretic, or penetration, losses. Current continuity requires that currents flow across the width of the tape through the matrix material, thus generating Joule heating. These "coupling" currents generate the coupling loss term.

Fig. 3 shows the two-phase loss data for PMC 4LB, wound to achieve uniform current distribution among the layers. The most notable aspect of this data set is the very strong uniformity in the *n* values compared to those for 4LA and the fact that they are all less than 3. The temperature and frequency dependencies of the losses are given in Table II.
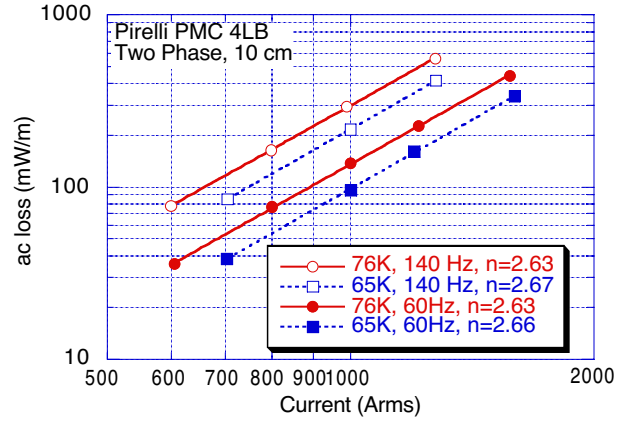

Fig. 3. Two-phase losses for PMC 4LB as a function of current at a conductor spacing of 10 cm and for the temperatures and frequencies indicated. The *n* values are the exponents of the power-law fits to the data shown in the figure.

The temperature dependence of the losses is again somewhat smaller than the critical state model would predict. However, the frequency dependence is much closer to the critical state result than is that for PMC 4LA.

Fig. 4. shows the results of measuring the two-phase losses for PMC 4LB at 1000 Arms at 76 K as a function of frequency. The upper curve in the figure shows the experimental results and an empirical fit to the data of the form (2) + (3). It is clear that the nonlinearity in the frequency dependence is quite small for this conductor.

The same fitting procedure was performed on a set of loss data for PMC 4LA taken under similar conditions. The parameters of these two fits are collected in Table III. The most striking difference is the much larger magnitude of the hysteretic term for 4LB. The magnitude of the coupling term at high frequency is very similar for the two conductors and overlaps within experimental precision. The value of the time constant τ may also differ by a factor of two, but its value is poorly defined, especially for 4LB, because of the small magnitude of the losses at low frequency that determine its value.
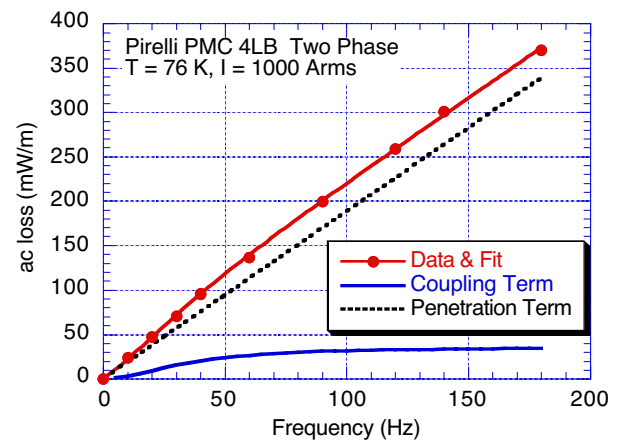

Fig. 4. Two-phase ac losses of PMC 4LB as a function of frequency at 76 K, 10 cm spacing, and 1000 Arms excitation current. The top curve shows both the data points and the fit to the data. The coupling term and penetration terms are the two contributions that are added to give the fitted loss curve.
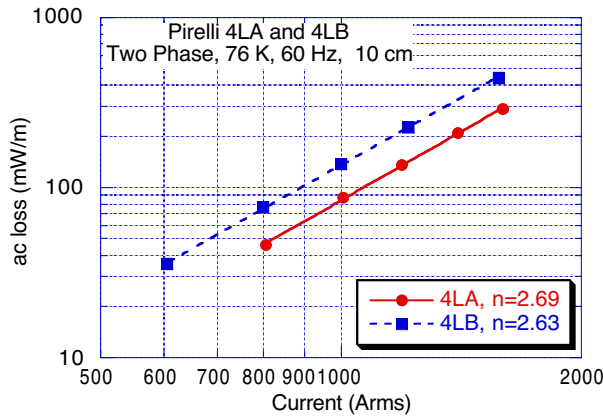
Fig. 5. Comparison of two-phase losses at the condition noted for PMCs 4LA and 4LB, with nonuniform and uniform current distribution, respectively. The *n* values are the exponents of the power-law fits to the data shown in the figure.

TABLE III.
PARAMETERIZATION OF LOSSES

Parameter	4LA	4LB
Slope of q_p term (mW/m-Hz)	0.82±0.02	1.88±0.04
High frequency limit of q_c term (mW/m)	43±3	35±7
τ (ms)	8.3±1	4.5±1.5

Comparing the two-phase losses of PMCs 4LA and 4LB as a function of current with other conditions held fixed, as shown in Fig. 5, the enhanced two-phase losses may also be seen readily. From the previous analysis of the frequency dependent data, it is clear that most of this difference is due to a larger hysteretic loss contribution for 4LB.

As a final point, a demonstration of the dependence of the two-phase losses on the magnitude of the applied magnetic field generated by the current flowing in the other conductors, we measured the losses in PMC 4LB with the separation between the conductors at both 10 cm and 20 cm. The magnetic field generated by the two other phases is proportional to *I*/*s* where *s* is the phase spacing. From Fig. 6, it can be seen that for a fixed current, doubling the phase spacing decreases the two-phase loss by a factor of ~6. If the losses are plotted as a function of the applied magnetic field, then it can also be seen that the losses depend only on the magnitude of the applied field.

IV. SUMMARY AND CONCLUSIONS

We have measured and analyzed the two-phase losses of two prototype multistrand conductors, designed as possible candidates for the Detroit Edison SPI retrofit cable project. Winding the PMC 4LB to produce a uniform current distribution (UCD) among the layers leads to an expected decrease in single-phase losses at currents greater than about
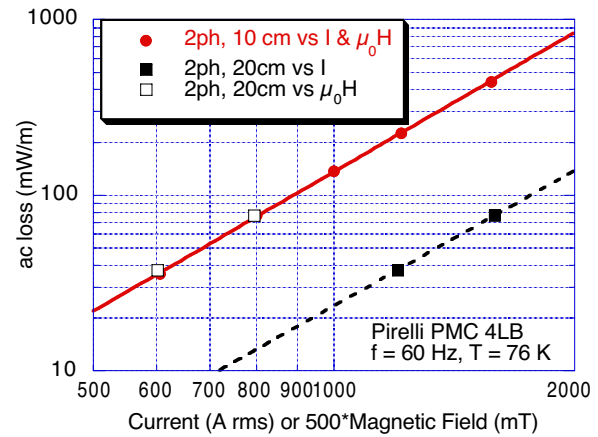

Fig. 6. Two-phase losses of PMC 4LB plotted as function of current and magnetic field for phase spacings of 10 cm and 20 cm.

I_c/2. The two-phase losses at a phase spacing of 10 cm, however, are enhanced for this winding configuration. Analysis of the frequency dependence of the losses shows that this enhancement is primarily due to extra hysteretic, and not coupling, losses in the PMC wound to achieve UCD. The source of this enhancement is the subject of further investigation. Increasing the phase separation distance to 20 cm leads to a large (factor of ~6) decrease in the two-phase losses and greatly reduces their influence on cable performance.

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